Reports on Geodesy and Geoinformatics, 2025, Vol. 119, pp. 1–6

DOI: 10.2478/rgg-2025-0001
Received: 22 September 2024 / Accepted: 2 January 2025
Published online: 24 January 2025

ORIGINAL ARTICLE

Practical analysis of using PPPH and raPPPid for Precise Point Positioning in Europe

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Abstract

Assessing the reliability of using open-source software packages for post-processing of the Global Navigation Satellite System (GNSS) is essential since GNSS modernization has the potential to assist satellite navigation users. The purpose of this study is to evaluate the accuracy of using two MATLAB-based programs, raPPPid and PPPH for precise point positioning in Europe. Data from 12 MGEX stations over two days were used, with one day dedicated to each of the 6 stations and a 30-second observation interval. The data were post processed by PPPH and raPPPid programs and a comparison was made to evaluate the results accuracy produced by each software and the ones acquired from MGEX stations. Convergence time was also estimated. By comparing the root mean square error (RMSE) values for North, East and Up directions estimated by PPPH and raPPPid, it was found that raPPPid gives more accurate results where the RMSE in N direction estimated by raPPPid varied from 0.5 cm to 1.9 cm; however, RMSE in N direction estimated by PPPH varied from 0.7 cm to 2.8 cm. RMSE in E direction estimated by raPPPid varied from 0.4 cm to 3.3 cm, but RMSE in E direction estimated by PPPH varied from 0.5 cm to 3.7 cm. RMSE in Up direction estimated by raPPPid varied from 0.8 cm to 5.2 cm, while RMSE in Up direction estimated by PPPH varied from 0.9 cm to 5.5 cm. 3D Positioning error was also estimated by both software and it was found that the 3D positioning error estimated by raPPPid varied from 0.2 cm to 2.2 cm, whereas the 3D positioning error estimated by PPPH varied from 0.9 cm to 4.1 cm. Finally, the average convergence time achieved by raPPPid was 16.5 minutes, while the average convergence time achieved by PPPH was 32 minutes.

Key words: GNSS, Precise Point Positioning (PPP), PPPH, raPPPid, Convergence time

1 Introduction

For users who require high-accuracy positioning, the precise point positioning (PPP) technique is thought to be an affordable and high-accuracy solution (El-Mewafi et al., 2019). Since it only requires one receiver and no reference station, the PPP technique has recently been refined and improved to attain the centimeter accuracy level at a reasonable cost and also with low-cost equipment. The PPP method can be used to detect changes in the troposphere and ionosphere layers, determine crustal movement, identify geoids, and determine a satellite's orbit (Huang et al., 2023). With the rapid development of the European system known as Galileo and the Chinese navigation system known as BeiDou, the PPP technique has emerged as one of the most important tools for Multi-GNSS Processing for all these applications. The PPP technique has been developed to improve the accuracy level based on the constellation and combination of all GNSS systems (Kandil et al., 2024). To take advantage of the potential benefits of the multi-constellation and multi-frequency GNSS, numerous software packages were developed and many of them are published and available at the GPS Toolbox of GPS Solutions journal (Herbert et al., 2020).

The aim of this study is to assess the performance of two of these software packages PPPH and raPPPid in Europe. Data from twelve MGEX stations in Europe will be processed by both software. 3D positioning error, RMSE for the three directions (N, E and Up) and the convergence time will be calculated by both software programs to compare them and to present which

Publisher: De Gruyter

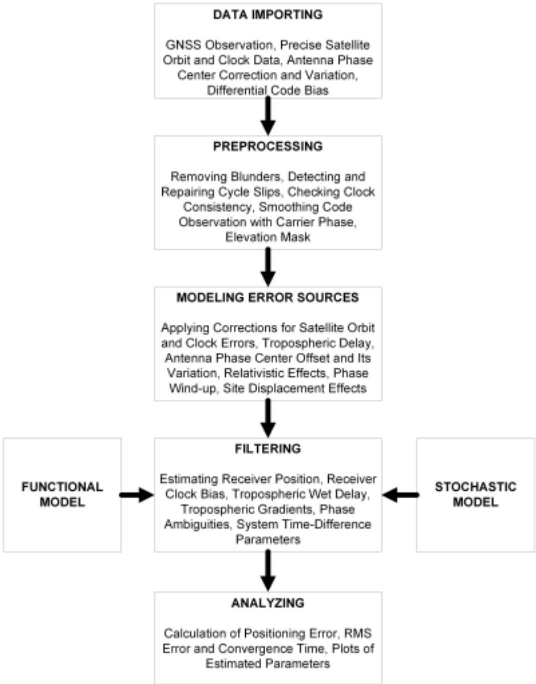

Figure 1. Main components of PPPH (Bahadur and Nohutcu, 2018)

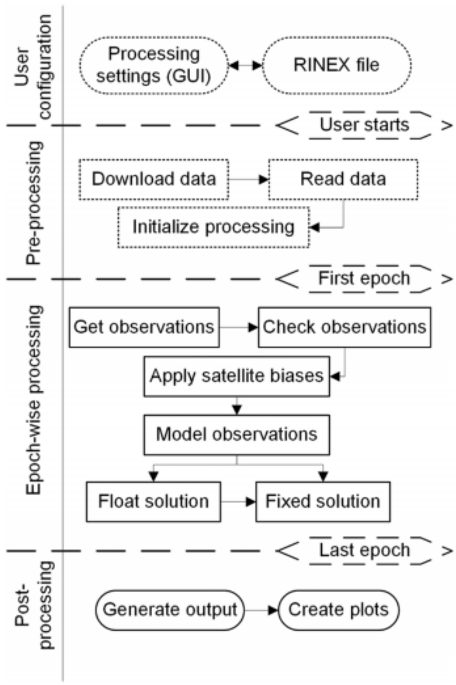

Figure 2. Main workflow of raPPPid (Glaner and Weber, 2023)

software performs better in the study area. A summary of both PPPH and raPPPid software will be introduced in the following section.

2 PPP Software Packages

2.1 PPPH

To capitalize on the potential benefits of the multi-constellation and multi-frequency GNSS, PPPH was created in the MATLAB environment. A GNSS analysis program called PPPH is capable of processing GPS, GLONASS, BeiDou, and Galileo observations to do multi-GNSS PPP analyses. The program is available at https://geodesy.noaa.gov/gps-toolbox/PPPH.htm. PPPH's intuitive graphical user interface (GUI) enables users to define the PPP process models, options, and parameters. Moreover, PPPH offers a number of analysis tools to evaluate the outcomes. Each of the five main PPPH components, as well as any related settings, is shown on a different tab in GUI. The PPPH working flowchart in Figure 1 illustrates the major parts and their roles. The last part is where the results are evaluated and presented. To create GNSS solutions, the first four components indicated make use of related theories and concepts (Bahadur and Nohutcu, 2018).

After completing the processing steps, the result file is generated and contains the estimated values for each epoch. Additionally, you can generate and process data relating to user-defined ground truth, such as convergence time, positioning error, and root mean square error, using the GUI's Analysis option. With PPPH, a wide variety of charts can be created to evaluate the epoch-by-epoch variations in estimated parameters and associated data, such as those for tropospheric zenith total delay, positioning error, receiver clock estimation, satellite number, and dilution of precisions (Bahadur and Nohutcu, 2018).

2.2 raPPPid

The raPPPid software package is written in Matlab and is an adaptable and user-friendly tool that is available at https://github.com/TUW-VieVS/raPPPid. This software can process GNSS observations with single, dual and triple frequencies in a variety of PPP techniques (such as the uncombined model and ionospheric-free linear combination). The user can choose from a wide range of satellite products, models, options, and parameters to fine-tune the PPP method. In this manner, high-to-low quality observation data from cell-phones and geodetic equipment can be handled by the software raPPPid. The convergence time of PPP remains a prominent topic in scientific research, even with notable advancements. With many applied methodologies, including PPP-AR or ionospheric pseudo-observations, raPPPid is specifically made to shorten the convergence period. It also provides users with a variety of charts and statistics to help them understand this crucial period.

Up to three frequencies from each of the four globally operational GNSS (GPS, GLONASS, Galileo, and BeiDou) can be processed by the MATLAB software package of raPPPid in several PPP models. The program design enables handling of both static and kinematic observation data with any interval, combining all GNSS and signals, and processing of various frequencies for each GNSS. The application supports the current GNSS file formats, such as ORBEX, and enables the automatic download of input data, such as a sizable number of satellite products and models. The output data are self-explanatory. Figure 2 shows the raPPPid primary workflow (Glaner and Weber, 2023).

3 Practical Study

The practical study is performed to cover Europe. Observation files are collected from https://cddis.nasa.gov/archive/gnss/data/daily. The data used are from twelve MGEX stations located in Europe. The MGEX stations are divided into two groups, each group

Table 1. PPPH and raPPPid software capabilities (Bahadur and Nohutcu, 2018; Glaner and Weber, 2023)

Capability	PPPH	raPPPid
Constellations	GPS, Galileo, GLONASS and BeiDou	GPS, Galileo, GLONASS, BeiDou and QZSS
Processing Mode	Static and Kinematic	Static and Kinematic
Products Entry	Entered manually to the software	Automatically downloaded
Frequency	Dual	Dual and Multi frequencies

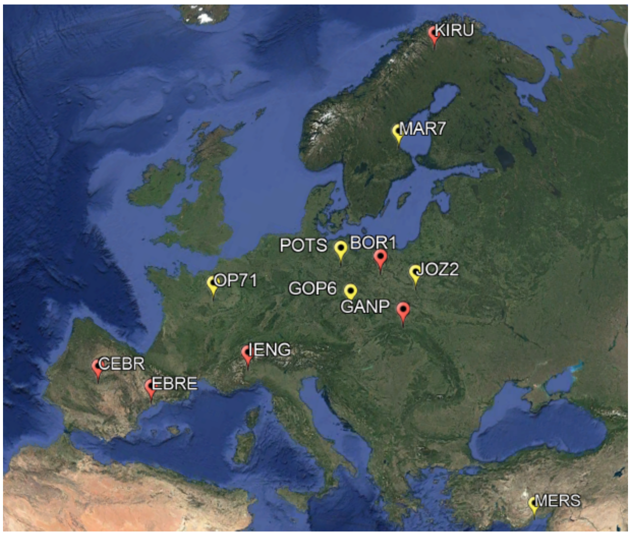

Figure 3. The used MGEX stations

consists of six MGEX stations. The MGEX stations are shown in Figure 3 and Table 2 shows where these stations are located and the used receiver in each one. The first group of MGEX stations are BOR1, CEBR, EBRE, GANP, IENG and KIRU with the red marks in Figure 3 and the observation day is DOY 01/2023. The second group of MGEX stations are JOZ2, MAR7, MERS, OP71, POTS and GOP6 with the yellow marks in Figure 3 and the observation day is DOY 65/2023. The used GNSS data in this study are processed using PPPH and raPPPid software. The practical study is performed in two days to assess the performance of the two software packages in different weather conditions and these two days are chosen because of the availability of observations data during them. The applied processing parameters are shown in Table 3.

Table 2. MGEX stations locations and receivers

MGEX Station	Country	Receiver Type
	First Group	
BOR1	Poland	TRIMBLE NITR9
CEBR	Spain	SEPT POLARX5TR
EBRE	Spain	LEICA GR50
GANP	Slovakia	TRIMBLE ALLOY
IENG	Italy	SEPT POLARX5TR
KIRU	Sweden	SEPT POLARX5TR
	Second Group	
JOZ2	Poland	TRIMBLE NITR9
MAR7	Sweden	TRIMBLE ALLOY
MERS	Turkey	LEICA GR50
OP71	France	SEPT POLARX5TR
POTS	Germany	JAVAD TRE_3
GOP6	Czechia	SEPT POLARX5

Table 3. Applied processing parameters by PPPH and raPPPid

Parameter	PPPH	raPPPid
Mode of calculation	Static	Static
Constellation	GPS+GLONASS +Galileo+BeiDou	GPS+GLONASS +Galileo+BeiDou
Frequencies	Dual	Dual
Observation type	Code and phase	Code and phase
Reference frame	ITRF14	ITRF14
Orbits/Clocks used	CODE Final	CODE Final
Antenna phase center offsets	IGS ANTEX File	IGS ANTEX File
Cut-off angle	8°	8°
Troposphere correction	Saastamoinen	VMF3
Ionosphere correction	Ionosphere-free linear comb.	Ionosphere-free linear comb.
Filtering	Kalman Filter	Kalman Filter Iterative

4 Results and Discussion

To evaluate the accuracy of PPPH and raPPPid, the 3D positioning error and Root Mean Square Error (RMSE) values are used in this evaluation as an accuracy indication, and convergence time also estimated in this process. The results of this evaluation process are shown in Tables 4 and 5 and Figures 4–13. In the context of this work, convergence time refers to the period required for a receiver to achieve an accurate position fix after being powered on or after a significant change in its position. This time can vary based on several factors, including the type of GNSS receiver, satellite visibility, atmospheric conditions, and the number of satellites in view. In general, achieving a 3D positioning error of within 10 meters is a common threshold for many applications, but specific requirements can vary based on the use case (e.g., navigation, surveying).

It has been noticed that raPPPid software provides more accurate results than PPPH for the most of the twelve used MGEX stations. The 3D positioning error estimated by raPPPid varied from about 0.2 cm to 2.2 cm, while the 3D positioning error estimated by PPPH varied from about 0.9 cm to 4.1 cm. RMSE in N direction estimated by raPPPid varied from about 0.5 cm to 1.9 cm, whereas RMSE in N direction estimated by PPPH varied from about 0.7 cm to 2.8 cm. RMSE in E direction estimated by raPPPid varied from about 0.4 cm to 3.3 cm, while RMSE in E direction estimated by PPPH varied from about 0.5 cm to 3.7 cm. RMSE in Up direction estimated by raPPPid varied from about 0.8 cm to 5.2 cm, whereas RMSE in Up direction estimated by PPPH varied from about 0.9 cm to 5.5 cm. The average convergence time achieved by raPPPid was 33 epochs, which equals 16.5 minutes, while the average convergence time achieved by PPPH was 64 epochs, which equals 32 minutes.

Table 4. 3D Positioning error, Root Mean Square Error in North, East and Up directions and Convergence Time estimated with PPPH and raPPPid for the first group of MGEX stations

Station	3D Pos. Error (cm)		N RMSE (cm)		E RMSE (cm)		Up RMSE (cm)		Con. Time (epoch)	
	PPPH	raPPPid	PPPH	raPPPid	PPPH	raPPPid	PPPH	raPPPid	PPPH	raPPPid
BOR1	2.8	1.3	2.8	1.8	2.7	3.3	1.3	1.4	70	31
CEBR	1.7	1.4	2.0	0.9	2.2	0.9	1.5	0.9	75	29
EBRE	1.0	2.2	0.8	1.4	1.3	0.7	1.4	1.4	50	31
GANP	4.1	1.3	2.5	1.9	0.9	2.7	1.9	0.8	59	33
IENG	1.6	1.3	1.9	0.8	1.5	0.4	0.9	1.1	60	30
KIRU	1.3	1.1	0.7	1.0	2.1	0.7	2.6	1.1	66	30

Table 5. 3D Positioning error, Root Mean Square Error in North, East and Up directions and Convergence Time estimated with PPPH and raPPPid for the second group of MGEX stations

Station	3D Pos. Error (cm)		N RMSE (cm)		E RMSE (cm)		Up RMSE (cm)		Con. Time (epoch)	
	PPPH	raPPPid	PPPH	raPPPid	PPPH	raPPPid	PPPH	raPPPid	PPPH	raPPPid
JOZ2	3.1	0.5	0.9	0.5	1.8	1.5	4.3	3.3	40	32
MAR7	1.6	0.7	1.2	0.7	0.5	0.7	3.2	3.5	75	49
MERS	1.7	0.9	0.7	0.8	1.7	1.0	1.0	4.5	79	27
OP71	1.1	0.2	0.9	1.0	2.0	1.0	3.9	5.2	77	32
POTS	3.5	0.5	2.8	1.5	3.7	2.3	5.5	5.2	64	46
GOP6	0.9	0.4	1.6	1.2	1.5	0.9	3.5	3.6	29	26

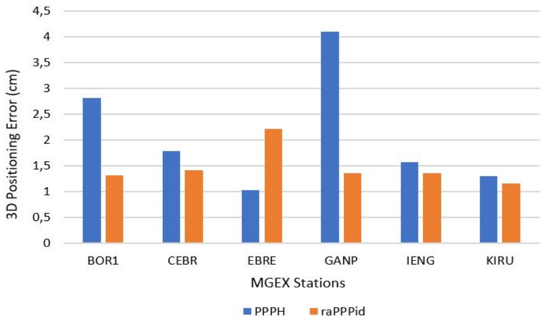

Figure 4. 3D Positioning Error in cm estimated with PPPH and raPPPid for the first group

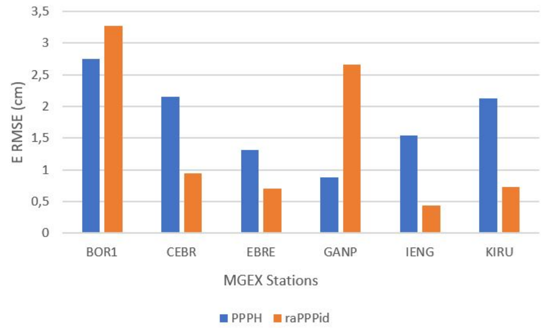

Figure 6. E RMSE in cm estimated with PPPH and raPPPid for the first group

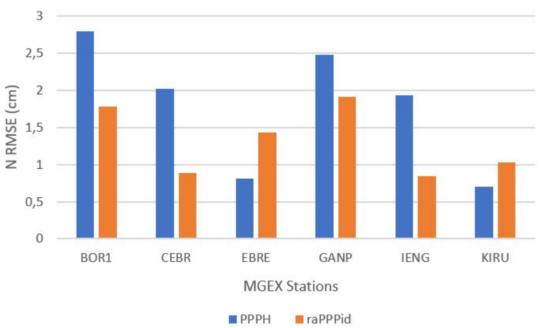

Figure 5. N RMSE in cm estimated with PPPH and raPPPid for the first group

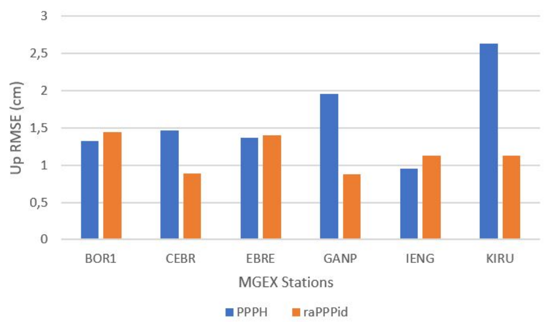

Figure 7. Up RMSE in cm estimated with PPPH and raPPPid for the first group

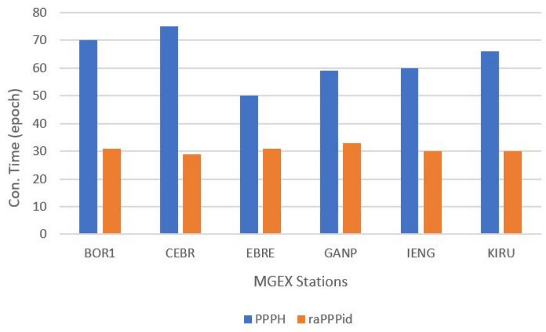

Figure 8. Convergence time for PPPH and raPPPid for the first group

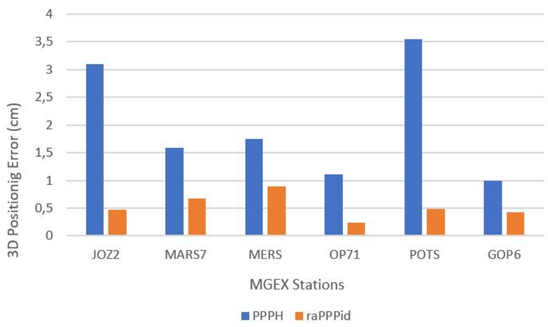

Figure 9. 3D Positioning Error in cm estimated with PPPH and raPPPid for the second group

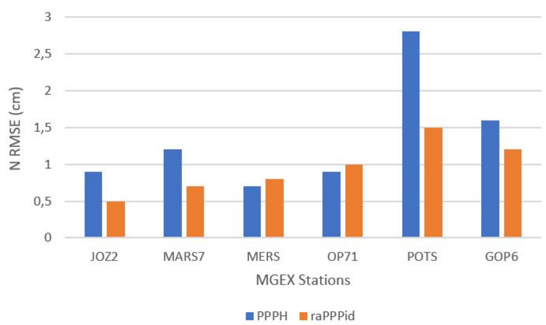

Figure 10. N RMSE in cm estimated with PPPH and raPPPid for the second group

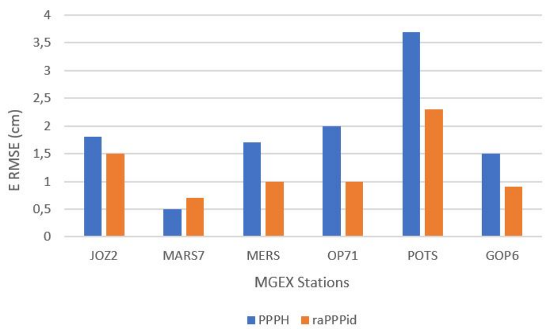

Figure 11. E RMSE in cm estimated with PPPH and raPPPid for the second group

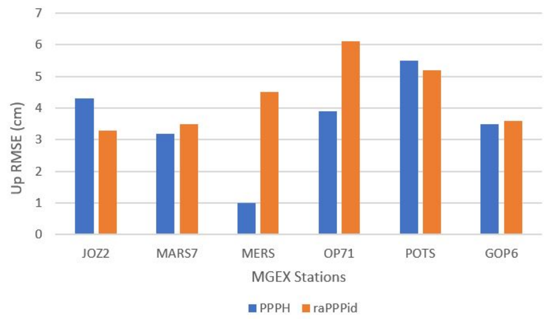

Figure 12. Up RMSE in cm estimated with PPPH and raPPPid for the second group

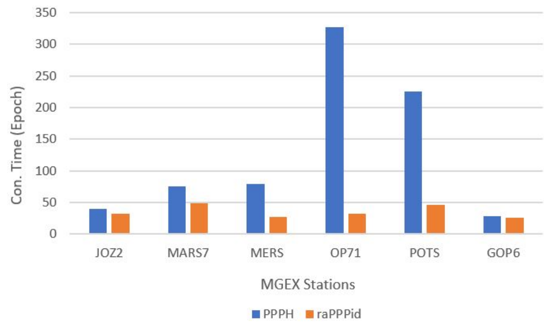

Figure 13. Convergence time for PPPH and raPPPid for the second group

5 Summary and conclusions

This study is performed to cover Europe and the used data are selected for twelve MGEX stations located in Europe and carried out for two days, one day for each 6 stations with an observation period of 30 seconds. The acquired data were post-processed using PPPH and raPPPid software packages. The coordinates generated from each software were then compared with the IGS final coordinates for the MGEX stations. Convergence time as previously mentioned was also calculated from both software. By comparing the root mean square error (RMSE) values for North, East and Up directions estimated by PPPH and raPPPid, it was found that raPPPid gives more accurate results as previously described in detail in the Results and Discussion section. 3D Positioning error was also estimated by both software to be used in the comparison and it was found that the 3D positioning error estimated by raPPPid varied from about 0.2 cm to 2.2 cm, while the positioning error estimated by PPPH varied from about 0.9 cm to 4.1 cm. Finally, the average convergence time achieved by raPPPid was 16.5 minutes, whereas the average convergence time achieved by PPPH was 32 minutes. It can be concluded that raPPPid clearly outperformed PPPH in most MGEX stations except for one station.

For future studies, it is recommended to perform an analysis of these software packages performance in kinematic solution.

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